

Evolution of the *Chandra* CCD Spectra of SNR 1987A : Probing the Reflected-Shock Picture

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ABSTRACT

We continue to explore the validity of the reflected shock structure (RSS) picture in SNR 1987A that was proposed in our previous analyses of the X-ray emission from this object. We used an improved version of our RSS model in a global analysis of 14 CCD spectra from the monitoring program with *Chandra*. In the framework of the RSS picture, we are able to match both the expansion velocity curve deduced from the analysis of the X-ray images and light curve. Using a simplified analysis, we also show that the X-rays and the non-thermal radio emission may originate from the same shock structure (the blast wave). We believe that using the RSS model in the analysis of grating data from the *Chandra* monitoring program of SNR 1987A that cover a long enough time interval, will allow us to build a more realistic physical picture and model of SNR 1987A.

Key words: supernova remnants - supernovae: individual (SNR 1987A) - X-rays: ISM

1 INTRODUCTION

After its reappearance in radio (Turtle et al. 1990; Staveley-Smith et al. 1992, 1993) and in X-rays (Beuermann et al. 1994; Gorenstein et al. 1994; Hasinger et al. 1996) at about 1000-1200 days after the explosion (DAE), SN 1987A entered into the phase of supernova remnant (SNR) formation (McCray 2007). Observations of this phenomenon from its onset give us a chance to study in detail the physics of strong shocks as well as to investigate the distribution of the circumstellar matter (CSM) around the exploded star. The latter may help us solve the mystery of the origin of the triple-ring system observed in the optical (Wampler et al. 1990; Jakobsen et al. 1991; Crotts & Heathcote 1991; Burrows et al. 1995). With this respect, X-ray observations are very important since they manifest most of the energetics at present and they provide us with direct information about the underlying physics of this evolving object.

The richness and variety of processes involved in the birth of SNR 1987A are manifested by observations across the entire electromagnetic spectrum. Radio observations

(Staveley-Smith et al. 1992, 1993, 2007; Ball et al. 2001; Manchester et al. 2002, 2005; Gaensler et al. 1997, 2007; Ng et al. 2008; Potter et al. 2009; Zanardo et al. 2010) tell us about the non-thermal (synchrotron) emission mechanisms and relativistic particle acceleration in strong shocks. Near-infrared observations tell us about the distribution of dust in the CSM and the physics of its interaction with the hot plasma (Bouchet et al. 2004, 2006; Dwek et al. 2008). Optical and UV observations (Sonnerborn et al. 1998; Lawrence et al. 2000; Pun et al. 2002; Sugerman et al. 2002; Groningsson et al. 2006, 2008) tell us about the physics of slow shocks and the distribution of dense clumps of gas.

The early evolution of SNR 1987A is strongly influenced by the distribution of circumstellar gas, which is concentrated in its triple-ring system. Although the origin of the ring system is not well understood, the colliding wind scenario that assumes a spherically-symmetric blue supergiant (BSG) wind interacting with an earlier emitted asymmetric red supergiant (RSG) wind seems the physically most reasonable explanation (Luo & McCray 1991; Wang & Mazzali 1992; Morris & Podsiadlowski 2007). It has been explored in detail by Blondin & Lundqvist (1993) who demonstrated that such a model is capable of accounting for the observed CSM characteristics, provided the RSG wind was highly asymmetric with most of its mass confined near the equa-

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tor. This picture needed an additional ingredient in order to explain the reappearance of SNR 1987A in radio and X-rays. Chevalier & Dwarkadas (1995) proposed that an extended HII region was formed inside the inner equatorial ring that was naturally produced by the photoionization of the shocked RSG wind (the inner ring) by the central progenitor BSG star. Based on this, Borkowski et al. (1997a, b) studied the complex hydrodynamics of the interaction of the SN ejecta with the CSM in vicinity of the inner ring that also predicts a continuous brightening of SNR 1987A in UV and X-rays.

Since its reappearance, SNR 1987A has been brightening continuously in X-rays with an accelerating rate in the past few years (Park et al. 2005, 2006, 2007; Racusin et al. 2009). The first spectrum of SNR 1987A with high spectral resolution was obtained with the high energy transmission grating on *Chandra* by Michael et al. (2002). The subsequent brightening has enabled dispersed spectra with good photon statistics to be obtained with both *Chandra* (Zhekov et al. 2005, 2006; Dewey et al. 2008; Zhekov et al. 2009) and *XMM-Newton* (Haberl et al. 2006; Heng et al. 2008). With the superb spatial and spectral resolution of the *Chandra* observatory, the first direct evidence was obtained that the distribution of the X-ray emitting plasma in SNR 1987A is not spherically-symmetric but it is ‘flat’, *i.e.*, it is concentrated in the vicinity of the equatorial ring (Zhekov et al. 2005, 2006; Dewey et al. 2008; Zhekov et al. 2009). These authors also showed that the bulk gas velocities deduced from the X-ray spectral lines are too low to account for the plasma temperatures inferred from the spectral fit, and showed that a simplified reflected-shock structure (RSS) model could match the observed spectra successfully.

Superb spatial resolution of *Chandra* allowed Burrows et al. (2000) to obtain the first image of SNR 1987A that showed a ring-like structure in X-rays. Subsequently, a monitoring program was established with *Chandra* to track the evolution of the X-ray images and CCD spectra of SNR 1987A. In addition to the continuing brightening in X-rays, the spectral data showed a gradual decrease of the plasma temperature behind the fast shocks. From the imaging data, we measured the expansion velocity of the remnant (Park et al. 2002, 2004, 2007). After applying a physically more realistic method to analyze the X-ray images, Racusin et al. (2009) obtained a more accurate expansion velocity curve. It showed clearly that the velocity started to decelerate after ~ 6000 DAE, about the same time that the X-ray light curve turned up (Park et al. 2005).

Here we analyze the evolution of the X-ray spectrum of SNR 1987A as observed with the pulse-height spectra obtained with the ACIS CCD camera during the monitoring program. One of the main goals of our study is to test the reflected-shock structure picture that emerged from analysis of the *Chandra* grating data. Since the pulse-height spectra have much better time coverage than the grating data, they can test whether is possible to match the CCD spectra and the expansion velocity curve in the framework of the RSS picture. In section § 2 we give a qualitative description of the RSS picture for SNR 1987A. In section § 3 we present details about the global RSS model. We describe the evolution of the CCD spectra and results from the spectral fits in sections § 4 and § 5, respectively. In section § 6 we discuss the results,

how they might be related to the non-thermal radio emission from SNR 1987A and the consistency of the global RSS picture. We present our conclusions in section § 7.

2 PHYSICAL PICTURE AND MOTIVATION

The physical picture that emerges from the analysis of SNR 1987A so far is the following. The circumstellar matter around the inner equatorial ring likely consists of at least two components: (1) a smooth gas component which represents the so called HII region (resulting from evaporation of the inner ring or being the hot bubble in the interacting stellar winds scenario); and (2) much denser clumps distributed within the smooth component. Although the origin of the dense clumps is unclear, it seems realistic to expect that they will form as a result from various dynamical instabilities. As Blondin & Lundqvist (1993) point out, in the interacting stellar winds scenario these instabilities are expected to produce a very clumpy and nonuniform shell. Thus, during the shell evolution dense clumps penetrate into the smooth component and form protrusions of various shapes.

Interaction of the SN ejecta with the smooth component gives rise to the standard two-slab structure bounded by a forward shock (blast wave compressing the smooth CSM component) and a reverse shock (compressing the ejecta material). The slabs are separated by a contact discontinuity.

When the blast wave overtakes a clump, it is ‘lit up’, namely, a transmitted shock starts to heat up the clump gas. At the same time, a reflected shock is sent back that shocks the gas behind the blast wave again, further increasing its temperature and decreasing its bulk velocity. Such a reflected-shock structure was invoked to explain the relatively narrow spectral lines detected by the *Chandra* grating observations of SNR 1987A and the corresponding simplified model was successful in describing these results. It should be kept in mind that the actual hydrodynamics of such an interaction is very complex: the clumps may have various shapes; the blast wave may wrap up around a clump and result in a more complicated shock structure; the reflected shocks from adjacent clumps may additionally interact to create a ‘turbulent’ system of gas shocked multiple times. A proper description of such interaction would require 3D hydrodynamic calculations. Thus, the RSS model might be considered as a very simple representation of the actual physical picture.

On the other hand, it does not seem feasible to attempt a complete match of the SNR 1987A observables (X-rays spectra, light curve etc.) by a detailed hydrodynamic model mostly because there are too many initial (and boundary) conditions to explore. Instead, we think it would be instructive to use a simplified model that bears the basic physics of this complex interaction and by using such a tool we hope to deduce valuable information about the CSM in the vicinity of the inner ring of SNR 1987A. Results from such an analysis of the available (and future) observations can guide us towards building a more realistic picture (and model) of this exciting phenomenon: the formation and development of SNR 1987A.

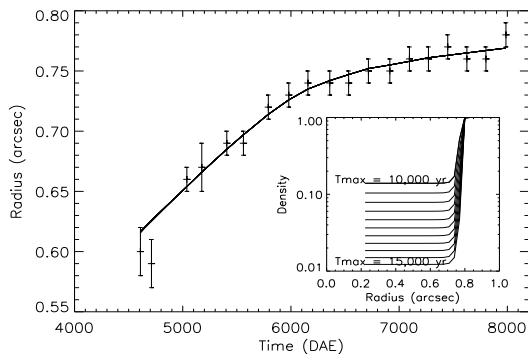


Figure 1. The analytical solution fits to the radial-expansion curve from Racusin et al. (2009). The solid line is an overlay of a few solutions having t_{max} from 10,000 to 15,000. The corresponding density profiles of the HII region are shown in the inset figure.

3 GLOBAL RSS MODEL

Zhekov et al. (2009) proposed a reflected-shock structure model to interpret the *Chandra* grating data for SNR 1987A taken in 2004-2007. It bears the basic physics of interaction of a shock with a dense clump which is a cornerstone in the physical picture described above. Since the CCD monitoring observations provide more extensive time coverage of the SNR 1987A evolution, they can be used to test details of this physical picture. To do so, we adopt the following improvements of the RSS model:

- At every moment (observation) the entire (integrated) X-ray characteristics of SNR 1987A can be represented with a RSS structure (blast wave, transmitted and reflected shocks), i.e., the blast wave is impinging on some average clump that is representative of the clumps at that radius from the center of the ring (the mean of the clumps distribution).
- The emission measure (EM) of the blast wave is not a free parameter from one observation to another but it follows the density profile of the smooth component ($EM \propto n^2 r^3$, where n is the density of the smooth component and r is the radius of the SNR 1987A at that moment).
- The SNR 1987A radius is calculated from 1D analytical solution that takes into account the density profile of the smooth component.
- The electron and ion temperatures are not equal behind the shocks (but see below).

3.1 Analytical solution

We anticipate that the density profile of the smooth component will be increasing steeply towards the inner ring radius as measured from the *Hubble Space Telescope* (*HST*) images. Many choices of such a function are possible and the model chosen here is:

$$\rho = \rho_0 + (\rho_{Ring} - \rho_0) \tanh \left(D \frac{r - R_0}{R_{Ring} - r} \right)^s \quad (1)$$

where $R_{Ring} = 0.83$ arcsec (Sugerman et al. 2002) is the radius of the equatorial ring; R_0 is the inner radius of the

HII region; ρ_{Ring} and ρ_0 are the densities respectively at these radii; D and s control the shape of the density profile. We assume that the outer supernova envelope has a density profile, $\rho \propto t^{-3}(r/t)^{-n}$, where $n = 9$ in the case of SNR 1987A (e.g., Eastman & Kirshner 1989; Suzuki et al. 1993; Borkowski et al. 1997a,b). Chevalier (1982) derived the solution for the structure that results from interaction of such a density profile with the circumstellar medium. Guided by his approach (i.e., using dimensional analysis), we derive an analytical solution for the radius, r , of the structure (the contact discontinuity). In the case of the CSM density profile given by eq. (1) we find:

$$t = t_{max} \left[\tilde{\rho}_0 + (1 - \tilde{\rho}_0) \tanh \left(D \frac{r - R_0}{R_{Ring} - r} \right)^s \right]^{\frac{1}{n-3}} \times \left(\frac{r}{R_{Ring}} \right)^{\frac{n}{n-3}} \quad (2)$$

where $\tilde{\rho}_0 = \rho_0/\rho_{Ring}$ and t_{max} is the time when the radius of the blast wave equals that of the ring.

We found that this expression for r is in satisfactory agreement with the result of a 1D hydrodynamic simulations for the case of stellar ejecta with $n = 9$ interacting with CSM that has density profile as given in eq. (1). This makes us confident in using the analytical solution in our model.

Figure 1 shows that equation (2) gives a good fit to the observed radial-expansion curve (Racusin et al. 2009). Note that there is not a unique set of fit parameters (t_{max} , $\tilde{\rho}_0$, D and s) that represents the ‘best’ fit. Namely, parameters t_{max} and $\tilde{\rho}_0$ cross talk and this is illustrated in Fig. 1 where the solid curve is in fact an overlay of a few solutions having t_{max} in the range from 10,000 to 15,000 DAE (the corresponding density profiles are shown in the inset figure). This behavior is well understood since the fit to the radial-expansion curve is determined by the relative change of the density of the smooth component between the observations. It will become possible to discriminate among different cases as the blast wave progresses further into the equatorial ring.

3.2 XSPEC model

Based on the analytical solution, we extended the RSS model for XSPEC¹ by Zhekov et al. (2009). The new RSS model tracks the radius of the blast wave that is inferred from the observations (Racusin et al. 2009). The emission measure behind this shock is scaled correspondingly ($EM \propto n^2 r^3$) and its ionization time ($n_e t$) follows the density profile of the preshock gas (in fact, its integral over time for a particular observation). Also, the blast wave velocity is estimated for each observation. Bearing in mind that the blast wave velocity has decreased recently from a few thousands km s^{-1} (Racusin et al. 2009) and the fact that the electron temperature of the X-ray emitting plasma was not greater than 3 keV (Park et al. 2006), we conclude that the electron and ion temperatures in the plasma behind the blast wave have not completely equilibrated (the mean plasma temperature $kT = 1.4 \times [V_{shock}/1000 \text{ km s}^{-1}]^2$ keV for the

¹ Version 11.3.2 of the XSPEC analysis package (Arnaud 1996) is used in this study.

SNR 1987A abundances). We recall that in the original RSS model, Zhekov et al. (2009) assumed a complete temperature equilibration (1T approximation) and took into account the non-equilibrium ionization (NEI) effects explicitly. Here we adopted the same approximation which can be justified by the following considerations.

First, a direct comparison between the X-ray spectra from a plane-parallel shock (PPS) model with different electron and ion temperatures (2T approximation; *vnps shock* in XSPEC) and from a 1T PPS model (*vp shock* in XSPEC) shows that the former model can be matched well by the latter having a postshock temperature averaged over the shock ionization age (see also Borkowski et al. 2001). This simply indicates that the NEI effects are more pronounced than the effects due to the electron temperature evolution downstream from the shock front. Second, we constructed a RSS model that correctly treats the temperature equilibration behind the shock (similarly as in *vnps shock* in XSPEC). But we found that its application to the entire set of monitoring observations is very unstable because the parameter space is too complicated.

Thus, the new RSS model correctly estimates the mean plasma temperature behind the blast wave. That result is then used to calculate the mean plasma temperature behind the transmitted shock (as well as behind the reflected shock; see Appendix B in Zhekov et al. 2009). The spectral fits assume an average electron temperature (\bar{T}_e) typical for either of the shocks. From these spectral fits we derive a parameter which is the average $\beta = \bar{T}_e/T$ (T is the mean plasma temperature) for each shock and its value sets an upper limit to the actual β in the shock front. We note that the reflected shock is assumed to have the same average β as the blast wave. As discussed by Zhekov et al. (2009), the plasma behind the reflected shock has quite complicated heating history. It is so since the reflected shock interacts with the plasma behind the blast wave that has already evolved for some time. As a result, in the region behind the reflected shock we have a mixture of hot plasma with different heating histories, resulting in a distribution of temperatures and ionization time scales. To simplify the model calculations and also due to the technical problems mentioned above, we adopted an *average* β parameter for the reflected shock that is equal to that in the blast wave.

4 CCD SPECTRA

The CCD spectra from the monitoring program of SNR 1987A are exactly the same (source and background spectra, redistribution and ancillary response functions) as in Park et al. (2006) and Park et al. (2007). Details of data reduction and spectral extraction are found therein. In this work we analyze 14 data sets, with *Chandra* ObsIds as follows: 122, 1967, 1044, 2831, 2832, 3829, 3830, 4614, 4615, 5579 and 6178, 5580 and 6345, 6668, 6669, 7636 (two of the observations were split into two subsets).

5 SPECTRAL FITS

As in previous studies of the *Chandra* spectra of SNR 1987A, we assumed that the X-ray absorption and abundances of

Table 1. The RSS Model Results (CCD Spectra)

| | | |
|--------------------------------|-----------------|-----------------------|
| χ^2/dof | 1706/1473 | |
| $N_H(10^{21} \text{ cm}^{-2})$ | 2.23 ± 0.05 | |
| H | 1 | 1 |
| He | 2.57 | 2.57 |
| C | 0.09 | 0.09 |
| N (1.63) | 0.32 ± 0.04 | 0.56 [0.50 - 0.65] |
| O (0.18) | 0.07 ± 0.01 | 0.081 [0.074 - 0.092] |
| Ne(0.29) | 0.22 ± 0.01 | 0.29 [0.27 - 0.31] |
| Mg(0.32) | 0.17 ± 0.01 | 0.28 [0.26 - 0.29] |
| Si(0.31) | 0.26 ± 0.01 | 0.33 [0.32 - 0.35] |
| S (0.36) | 0.36 ± 0.02 | 0.30 [0.24 - 0.36] |
| Ar | 0.537 | 0.537 |
| Ca | 0.339 | 0.339 |
| Fe(0.22) | 0.10 ± 0.01 | 0.19 [0.19 - 0.21] |
| Ni | 0.618 | 0.618 |

Note – Results from the *simultaneous* fit to 14 CCD spectra of SNR 1987A. The uncertainties are 1σ errors from the fit. All abundances are expressed as ratios to their solar values (Anders & Grevesse 1989). For comparison, the inner-ring abundances of He, C, N, and O (Lundqvist & Fransson 1996) and those of Ne, Mg, Si, S and Fe typical for LMC SNRs (Hughes et al. 1998) are given in the first column in parentheses. The Ar, Ca and Ni abundances are representative for LMC (Russel & Dopita 1992). The derived abundances (with 90% confidence interval in brackets) from the analysis of the *Chandra* grating spectra (Zhekov et al. 2009) are given in the third column.

the hot plasma do not change with time. Thus, all spectra shared the value for N_H and had the same abundances. The procedures for fitting abundances are the same as those described in Michael et al. (2002). Namely, we only varied the abundances of elements having strong emission lines in the observed (0.5 - 4 keV) energy range: N, O, Ne, Mg, Si, S and Fe.

To fit the global RSS model to the data we adopt the following procedure. We choose one of the density profiles in the HII region that provides a good fit to the expansion velocity curve (Fig. 1). For the results presented here we used the case with $t_{max} = 13,000$ DAE and $\tilde{\rho}_0 = 0.0289$ ($\tilde{\rho}_0 = \rho_0/\rho_{Ring}$). We held these parameters fixed in the fits. Consequently, we know the evolution of the emission measure ($EM \propto n^2 r^3$) and ionization time ($n_e t$) of the blast wave, but in relative units. We derive and their absolute calibration from the fits. From the analytical solution we also know the velocity of the blast wave which in turn determines the mean plasma temperature behind this shock. For each observation, we fitted for the average β which is a free parameter. We derive the mean plasma temperature in the transmitted shock self-consistently as described in Appendix B in Zhekov et al. (2009) and we only fitted for the average electron temperature in this shock. For each observed spectrum we fitted both the emission measure and ionization age of the transmitted shock. The RSS model also estimates all the parameters (and the spectrum) of the reflected shock in a self-consistent way.

The global RSS model was used to fit 14 CCD spectra simultaneously. Figure 2 shows that the RSS model is very successful in representing the X-ray emission from SNR 1987A. Other fit results are given in Table 1, Figs. 3 and 4. One can see that some shock parameters follow the

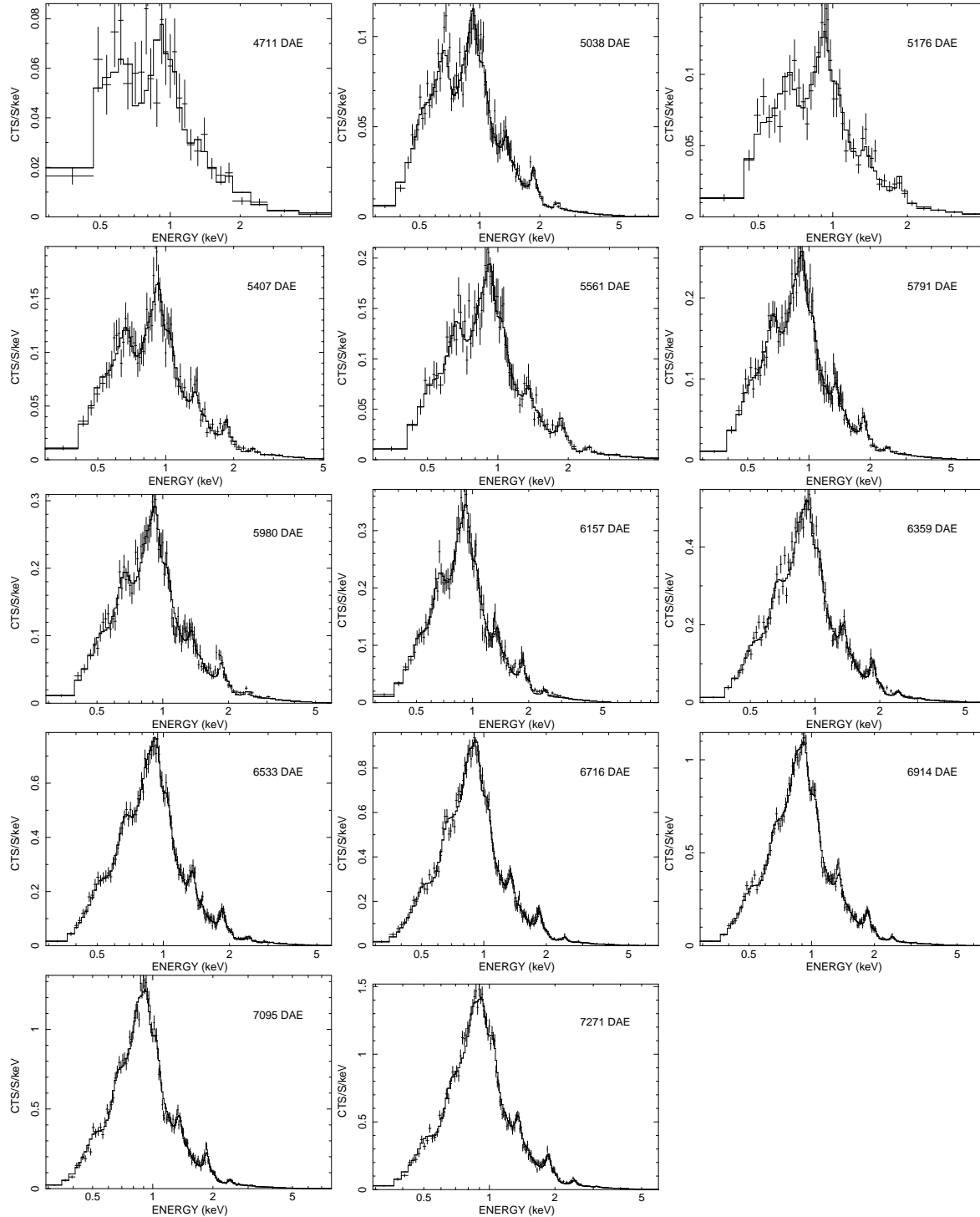


Figure 2. The background-subtracted spectra of SNR 1987A overlaid with the model fits for the case with $t_{max} = 13,000$ DAE (see § 5). Each panel is marked by the days after explosion of the corresponding observation. All the spectra are re-binned to have a minimum of 50 counts per bin but the observations at 4711 DAE (20 cts/bin) and at 5178 DAE (30 cts/bin).

same pattern as derived in previous analyses (e.g. Park et al. 2006) but their values are derived now in the framework of a (highly simplified) *physical* model. For example, the average electron temperature in the blast wave decreases gradually, while the mean electron temperature behind the transmitted shock increases slightly. These results are consequences of the increasing preshock density and the corre-

sponding decreasing shock velocity, which helps the electron temperature equilibration. As Figure 4 shows, the blast-wave emission measure increases smoothly at an accelerating rate. In contrast, the emission measure of the transmitted and reflected shocks increases suddenly for epochs after ~ 6200 (6000–6400) DAE in coincidence with the steep up-turn in the X-ray LC (Park et al. 2005) and the decrease in

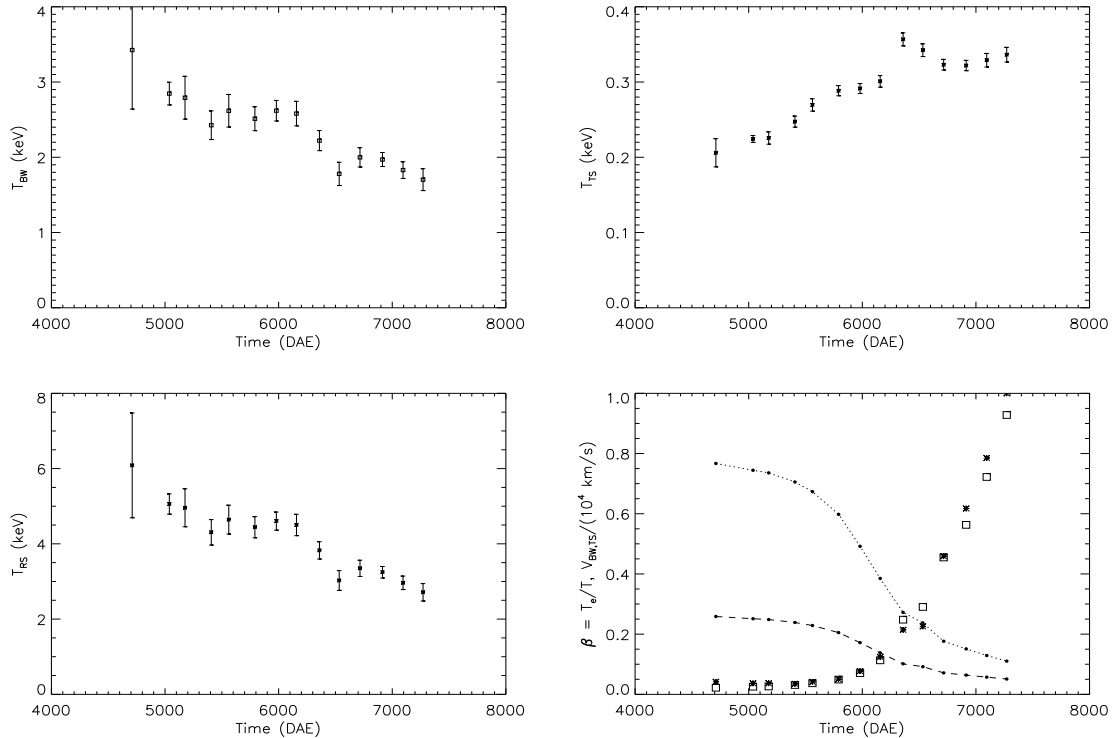


Figure 3. Evolution of various shock parameters as derived from the global RSS model fit. Shown are: the average electron temperatures for the blast wave, transmitted and reflected shocks (see text for details). The lower right panel represents the ratio of the average electron to the mean postshock temperature for the blast wave (squares) and the transmitted shock (asterisks). For comparison the blast wave velocity is denoted with dots and a dotted line, while the velocity of the transmitted shock is depicted with dots and a dashed line. The error bars in the temperature plots are 1σ errors from the fit. BW, TS and RS stand respectively for the blast wave, transmitted and reflected shock.

the expansion velocity curve of SNR 1987A (Racusin et al. 2009). This behavior is probably a consequence of the fact that the number of dense clumps overtaken by the blast wave started to increase at those times. Future observations will tell us about their distribution deeper in the equatorial ring. Also, Figure 4 shows the ionization ages ($n_e t$) for each RSS component. We note that the high values for the transmitted shock in the early observations likely result from numerical uncertainties due to the small contribution of this component to the total X-ray emission. Thus, we consider these ($n_e t$) values less reliable.

Note that on average the derived abundances have smaller values than the ones derived from analysis of the grating data (Dewey et al. 2008; Zhekov et al. 2009). This result is likely an artifact of the diminished resolution in the CCD spectra. Figures 5 and 6 show how the RSS model matches the X-ray light curve in the ‘soft’ (0.5–2 keV) and ‘hard’ (3–10 keV) energy bands. All the fluxes are from Park et al. (2006) and Park et al. (2007). We see that the emission from the blast wave dominated the soft X-ray light curve until the turning point mentioned above, ~ 6200 (6000 – 6400) DAE, after which time the emission from the transmitted shock became dominant. On the other hand, the blast-wave emission continued to dominate the hard X-ray light curve after the turning point, augmented by an increasing contribution from reflected shocks.

Interestingly, the (0.5–2 keV) model flux, extrapolated

back to *ROSAT* times, matches those SNR 1987A fluxes as well. This extrapolation assumes that at that time the entire X-ray emission was formed in the blast wave. Therefore, the blast wave flux from the first *Chandra* observation was scaled back with the emission measure of the blast wave ($EM \propto n^2 r^3$) which is known from the analytical solution. This result gives us more confidence in the global RSS model.

Figure 3 shows that the average β ($\beta = \bar{T}_e/T$) for the blast wave gradually increases as the shock velocity decreases. This behavior is similar to the one for the ratio of the electron and ion temperature set at the shock front being reversely proportional to the Alfvén Mach number of the shock (e.g. Ghavamian et al. 2001). The velocity evolution of the average β can likely be attributed to this fact as well as to the increasing ionization age of the blast wave. However, one should keep in mind that the actual physical picture is not that simple since any new gas parcel that is overtaken by the blast wave does *not* follow exactly the evolution of the previous gas parcels and has its own evolution instead.

Note also that the average β of the transmitted shock follows exactly the same pattern as that for the blast wave. We regard this result with caution: it might just be a coincidence that the values of the two β ’s are about the same since although relatively high the velocity of the transmitted shock is considerably lower than that of the blast wave.

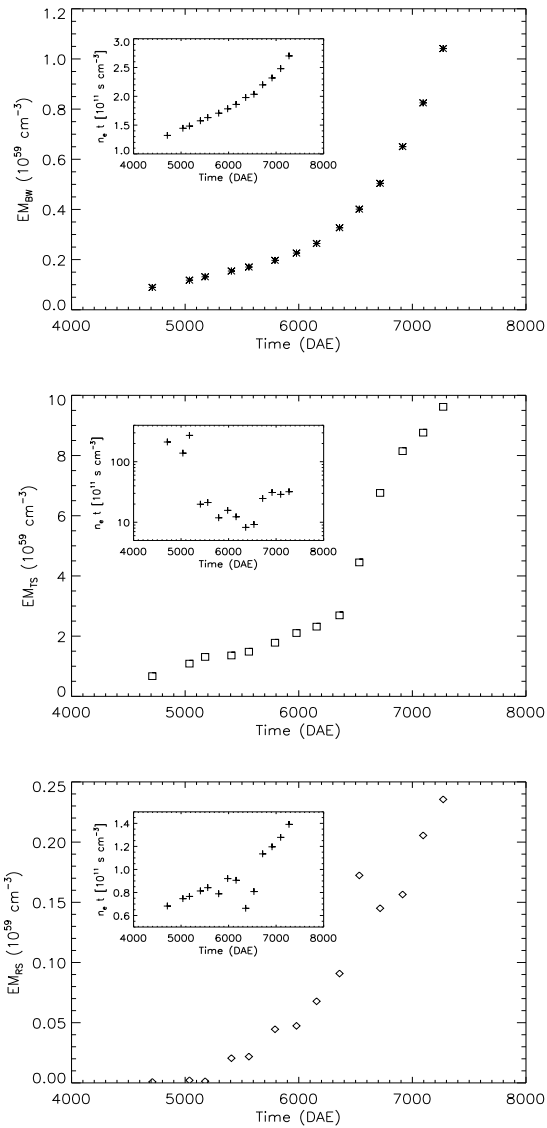


Figure 4. Emission measure of the shock components as derived from the global RSS model fit. BW, TS and RS stand respectively for the blast wave, transmitted and reflected shock. The corresponding ionization ages are shown in the inset figure of each panel.

Summarizing the basic results, we note that the global RSS model provides a simple unified physical picture that can match the observed expansion of the X-ray image as well as the X-ray light curve and spectral evolution of SNR 1987A. We are encouraged to believe that by using the RSS model to analyze the data from the ongoing monitoring of this object with *Chandra* we may deduce further details, not only about CSM, but also about the kinematics of the X-ray emitting plasma. Moreover, we are hopeful that the information derived from the RSS model analysis of the X-rays from SNR 1987A may be used in conjunction with observations at other wavelength bands (e.g., radio, infrared) to further constrain the model.

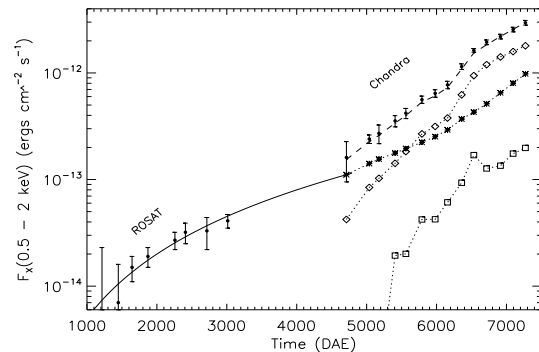


Figure 5. The soft X-ray LC of SNR 1987A from *ROSAT* and *Chandra*. The data with error bars are from Park et al. (2007). Components of the RSS model are marked with: asterisks (the blast wave); diamonds (the transmitted shock); squares (the reflected shock). The solid line denotes the extrapolation from the first *Chandra* observation back to the *ROSAT* times under the assumption that all the X-ray emission is due to the blast wave alone.

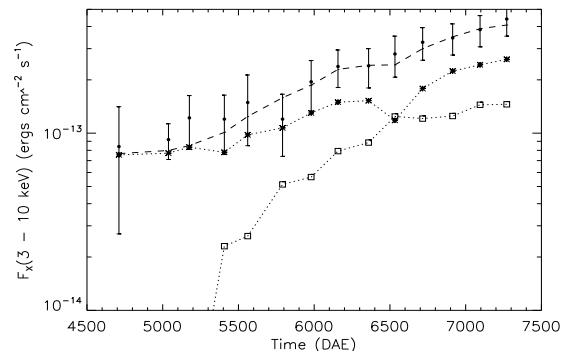


Figure 6. The hard X-ray LC of SNR 1987A from *Chandra*. The data with error bars are from Park et al. (2007). Components of the RSS model are marked with: asterisks (the blast wave) and squares (the reflected shock). The contribution of the transmitted shock is very low and thus it is out of the shown range on the y-axis.

6 DISCUSSION

6.1 X-rays vs. Radio Emission

X-rays from SNR 1987A are of thermal origin and they provide us with direct information about the strong shocks in this object. On the other hand, the radio emission from SNR 1987A is non-thermal synchrotron radiation (e.g. Staveley-Smith et al. 1992), which requires two ingredients: relativistic electrons and a magnetic field. The relativistic electrons are assumed to be born in strong shocks through the mechanism of diffusive shock acceleration (DSA). Thus, the non-thermal (NT) radio emission can provide us with additional details about the physical picture in SNR 1987A.

An interesting question is whether the X-rays and NT radio emission originate from the same shocks. In what follows, we assume that this is indeed the case, specifically, that the radio emission comes from the blast wave in SNR 1987A. To explore this possibility, we adopt an approach similar to

the one we took in the analysis of the CCD X-ray spectra above. Namely, we adopt a simple model for the NT radio emission and derive some parameters of the relativistic electrons involved in this process. Because it is not possible to measure the magnetic field directly, we assume that it is proportional to the density of the shocked plasma (frozen-in conditions).

The light curves (LC) of SNR 1987A at four radio frequencies were taken from Zanardo et al. (2010). Under the assumption that this is synchrotron emission from relativistic electrons having a power-law distribution in energy, the LCs were fitted simultaneously with a power-law function whose normalization and power-law index are function of time:

$$F_\nu(t) = F_0(t) \nu_{\text{GHz}}^{\alpha(t)} \quad (3)$$

where ν_{GHz} is the radio frequency in GHz, $F_0(t)$ is the flux at 1 GHz in mJy and $\alpha(t)$ is the power-law index. The parameters $F_0(t)$ and $\alpha(t)$ were characterized as a sum of Chebyshev polynomials of up to the 6-th power: $F_0(t) = \sum a_j \text{Cheb}_j$, $\alpha(t) = \sum b_j \text{Cheb}_j$. We note that such a characterization allows deriving the power-law index even if the data at different frequencies are not taken exactly at the same time.

The fits to the radio LCs and the derived flux normalization (F_0) and power-law index (α) are shown in Fig. 7. Note that the variations of the power-law index are similar to those derived in the original analysis of these data (Manchester et al. 2002; Staveley-Smith et al. 2007; Zanardo et al. 2010). Next we interpret these results by considering the basic model (Bell 1978) for diffusive shock acceleration of relativistic electrons and the theory of synchrotron emission (Rybicki & Lightman 1979).

In the framework of the DSA model, the resultant relativistic particles have a power-law distribution in energy and the corresponding power-law index is (eq. [12] in Bell 1978):

$$p = \frac{(2 + d_{ju}) + d_{ju}(2V_w/V_{sh} - 1/M_A)}{(d_{ju} - 1) - d_{ju}(V_w/V_{sh} + 1/M_A)} \quad (4)$$

where d_{ju} is the density jump at the shock front, V_{sh} is the shock velocity, V_w is the velocity of the turbulent waves downstream and M_A is the Alfvén Mach number of the shock. We note that for strong adiabatic shocks (as expected in SNR 1987A) the density jump is $d_{ju} = 4$ for gas (plasma) with adiabatic index $\gamma = 5/3$. Thus, three limiting cases are possible: (i) shocks with large Alfvén Mach number and turbulent waves which have quickly isotropised ($V_w \ll V_{sh}$, $M_A \gg 1$); (ii) strong shocks with similar turbulent waves as above but with Alfvén Mach number not much larger than unity ($d_{ju} = 4$, $V_w \ll V_{sh}$, $M_A > 1$); (iii) strong shocks with large Alfvén Mach number and turbulent waves that have not isotropised yet ($d_{ju} = 4$, $V_w/V_{sh} \neq 0$; $M_A \gg 1$).

The corresponding results for these three limiting cases are shown in the two upper panels of Figure 8. We made use of the relation between the spectral index of the resultant synchrotron emission from relativistic electrons with a power-law distribution in energy, $\alpha = -(p - 1)/2$ (Rybicki & Lightman 1979). In case (i), we see that the density jump at the shock(s) in SNR 1987A is smaller than its canonical value ($d_{ju} = 4$) for strong shocks. This may in-

dicate that efficient particle acceleration influenced the hydrodynamic structure of the shock(s). If so, the derived values for the density jump correspond to the subshock while the total compression (for the downstream versus upstream gas) is greater than 4 (e.g., for the case of SNR 1987A see Berezhko & Ksenofontov 2006; Duffy et al. 1995). In case (ii), we see that the Alfvén Mach number has a tendency to increase with time. We note that the opposite is expected if the blast wave penetrates further on in the HII region near the inner ring and the magnetic field is subject to the frozen-in conditions (being proportional to the density). In case (iii), we see that after an initial increase the turbulent waves velocity is decreasing which may indicate that they evolve towards equilibrium — that is they tend to isotropize with time.

On the other hand, the fits to the radio LCs of SNR 1987A tell us the time evolution of the normalization for its flux (F_0) which in turn can be used to deduce some valuable information about the relativistic electrons, magnetic field etc. From equation (6.36) in Rybicki & Lightman (1979) and for a distance of 50 kpc to SNR 1987A we can write:

$$F_0 = 4.272 \times 10^{11} \frac{n_{\text{tot}}^{(r)} \tilde{V} B^{1-\alpha} \Gamma_1 \Gamma_2 C_0^\alpha (-2\alpha)}{2(1-\alpha)} \quad (5)$$

where F_0 is in mJy; $n_{\text{tot}}^{(r)}$ is the total number density of the relativistic electrons; $\tilde{V} = V(t)/V_R = (r/R_{\text{Ring}})^3 \Delta$ is the volume occupied by the shocked gas (and relativistic electrons), that is between the blast wave and the contact discontinuity, in relative units and $\tilde{\Delta} = \Delta r/r$ is the relative thickness of that volume; B is the magnetic field strength in Gauss ($B = B_0 \frac{r}{r_0}$ - frozen-in conditions, the subscript 0 denotes parameters at the inner radius of the HII region); $C_0 = (2\pi m_e c/3e) \times 10^9 = 119.119$ is a constant (m_e, e are the electron mass and charge, c is the speed of light, while the factor 10^9 comes from using the radio frequencies in GHz); $\Gamma_1 = \Gamma(\frac{p}{4} + \frac{19}{12})$ and $\Gamma_2 = \Gamma(\frac{p}{4} - \frac{1}{12})$ as Γ is the gamma function.

Thus, from eq. (5) and the fit results for the radio LCs, we can derive the time evolution of the mean number density of relativistic electrons. We recall that the radius of the blast wave, and the preshock density profile are those used in the fits to the X-ray CCD spectra of SNR 1987A. The relativistic number density can then be used to estimate the pressure of relativistic electrons in the radio-emitting region. Figure 8 presents results for a nominal set of values for the preshock nucleon density and magnetic field at the inner radius of the HII region ($n_0 = 100 \text{ cm}^{-3}$, $B_0 = 1 \text{ mG}$) and thickness (e.g., $\tilde{\Delta} \approx 0.1$). We recall that the gas pressure behind the shock is $p_g = 3/4 \rho_0 V_{sh}^2$ ($\rho_0 = 1.6 m_p n_0$ for the SNR 1987A abundances, m_p is the proton mass). We see that neither the pressure of relativistic electrons nor the magnetic field pressure is a significant fraction of the thermal gas pressure. This indicates that the model of standard strong shocks can explain both the observed X-ray and radio emission from SNR 1987A. Also, the small magnetic pressure is a sign of large Alfvén Mach numbers, thus, case (iii) mentioned above seems a realistic option for the corresponding physical picture, and future observations will show us if this picture may evolve to being intermediate between cases (ii) and (iii).

From eq. (5) and the fit results for the radio LCs, we

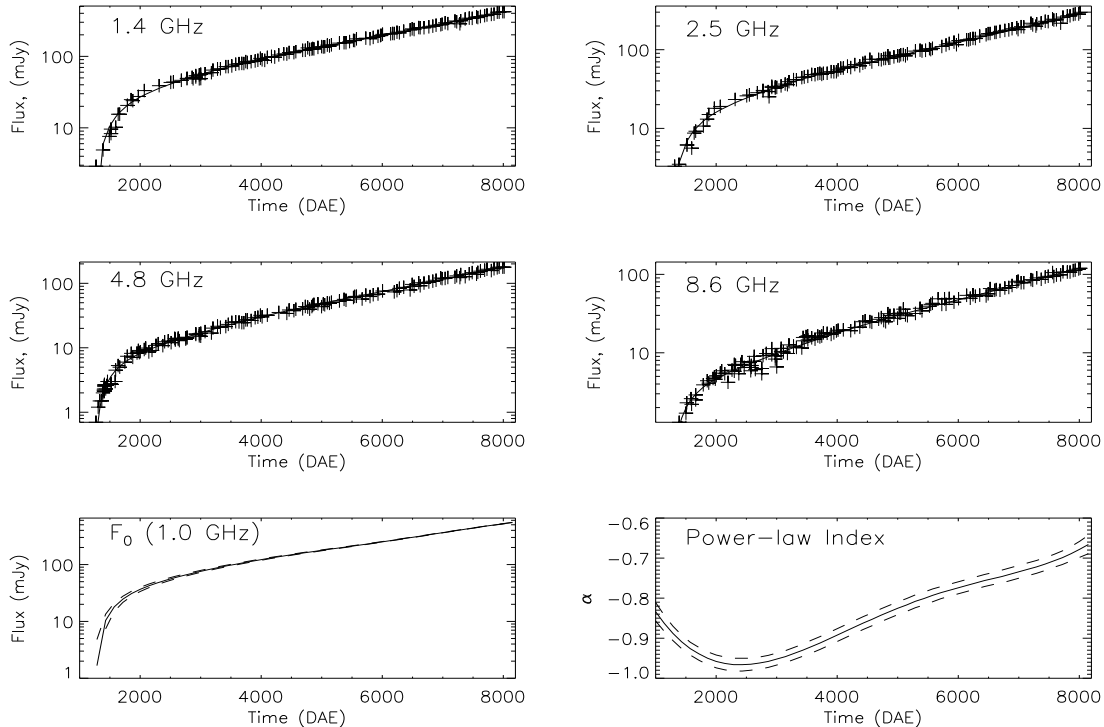


Figure 7. The radio LCs (pluses) of SNR 1987A (from Zanardo et al. 2010) and their model fits with eq.(3) (solid line). The model parameters, flux normalization at 1 GHz (F_0) and spectral index (α), are shown in the bottom two panels. The dashed lines represent the corresponding 1σ errors from the fit. The rms from the entire fit is 3.9 mJy while its value for the individual frequencies is 4.8 mJy (1.4 GHz), 5.2 mJy (2.4 GHz), 2.8 mJy (4.8 GHz) and 2.4 mJy (8.6 GHz).

can also estimate the time evolution of the total number of relativistic electrons in the shock region and some related quantities. Namely, the total number of particles is $n_{tot}^{(r)} \tilde{V} = N(t) = N(t_0) + \tilde{N}(t)(t - t_0)$, where $\tilde{N}(t)$ is the time-averaged production rate of relativistic electrons. Since the relativistic particles are accelerated at the shock front and then injected into the postshock region, we could also write: $N(t) = N(t_0) + n_{in}^{(r)} u_2 S \Delta t$, where $n_{in}^{(r)}$ is the number density of the injected relativistic electrons, S is the shock surface ($S \propto [r/R_{Ring}]^2$) and according to the DSA model: $u_2 = V_{sh}/4 + V_w$ for strong shocks (Bell 1978). Figure 8 presents the time evolution of $N(t)$ and $n_{in}^{(r)}$ based on the fits to the radio LCs and for case (iii). We see that after an initial steep increase of the newly born relativistic electrons, their average production rate follows a gradual decline. Note also that the number density of the newly injected relativistic electrons, normalized to the local preshock density, follows a similar pattern. We tentatively attribute this decline to decreasing efficiency of particle acceleration in the decelerating shocks. We believe that this behavior may be an important clue to the details of the particle acceleration mechanism that operates in SNR 1987A. Such details might be helpful to build a physically more sophisticated model of this system.

6.2 Overall Consistency of the Global RSS Picture

As a further constraint on this picture and as a check on its internal consistency, we can use the results from the fits to the CCD X-ray spectra of SNR 1987A. Namely, the preshock nucleon number density can be deduced from the emission measure of the blast wave and a density jump for strong adiabatic shocks ($d_{ju} = 4$). For distance of 50 kpc to SNR 1987A the X-ray fits yield a nucleon number density at the inner radius of the HII region: $n_{0,X} = (49.2 \pm 1)/\sqrt{\sin \theta}$, cm^{-3} , where θ is the opening half-angle of the inner ring ($\theta = \pi/2$ gives a complete spherical shell). Recall that we have a clear evidence based on the spatial-spectral effects in grating spectra that the X-ray emission in SNR 1987A is confined in the equatorial plane although the opening angle of the X-ray emission region is not yet well constrained (Zhekov et al. 2005, 2006; Dewey et al. 2008; Zhekov et al. 2009). On the other hand, the triple-ring system observed in the optical (Burrows et al. 1995) is solid evidence for a highly asymmetric distribution of the circumstellar matter around the exploded star in the center of SNR 1987A. Although the origin of this asymmetry is not yet well understood, the scenario of colliding stellar winds that considers a spherically symmetric BSG wind impinging onto an asymmetric RSG is probably the most realistic model so far. Blondin & Lundqvist (1993) investigated this scenario in detail and their ‘best’ model, which correctly predicts various parameters of the circumstellar environment prior to the explosion of SN 1987A, requires that 50% of the RSG

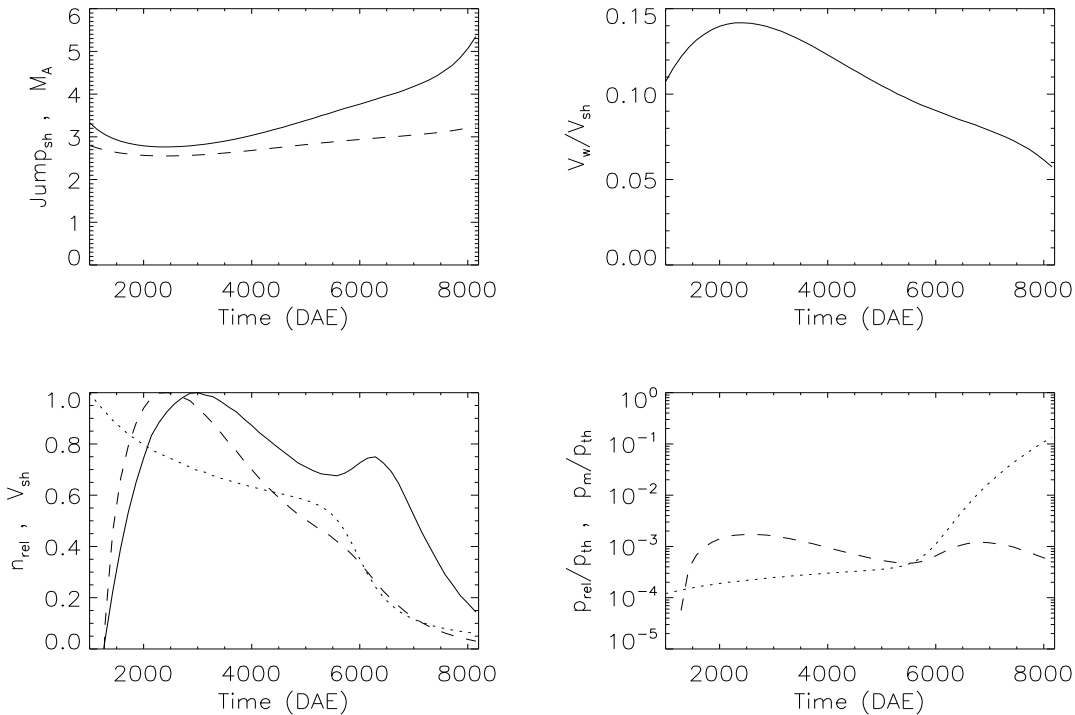


Figure 8. The radio LC fit parameters of SNR 1987A. The *Upper Left* panel: the Alfvén Mach number (solid line) and the density jump (dashed line). The *Upper Right* panel: the turbulent velocity. The *Lower Left* panel: the time-averaged production rate of relativistic electrons (dashed line), the number density of the injected relativistic electrons (solid line) and the blast wave velocity (dotted line) as all these are normalized to their maximum value for clarity. The *Lower Right* panel: the ratios of the pressure of relativistic electrons (dashed line) and magnetic pressure (dotted line) to the thermal pressure behind the blast wave. See text for details.

wind mass is collimated within $\sim 10^\circ$ from the equatorial plane. We thus see that the nucleon density of the HII region that is deduced from the analysis of the CCD X-ray spectra is $n_{0,X} = 118 \pm 2.5, \text{ cm}^{-3}$. This value is consistent with the one assumed for the estimates presented in Fig. 8.

From these considerations we conclude that the case of strong adiabatic shock(s) is suitable for explaining both the X-ray and radio emission from SNR 1987A and that further analysis of the newly obtained data along the same lines might be indeed helpful in building a realistic picture of this object. It is worth noting, though, that this is indeed the case provided the DSA of heavy particles is not as efficient as the one for the electrons in SNR 1987A. For example, if the relativistic protons gain the same amount of energy from the blast wave as supplied into relativistic electrons the picture will remain the same. But, if the DSA is very efficient and produces relativistic protons (or nuclear cosmic rays) and electrons with similar densities, the total pressure of all the relativistic particles will be comparable to the thermal gas pressure and the physical picture will be more similar to case (i) as described above. We recall that in such a case the blast wave in SNR 1987A will be affected by the feedback from the relativistic particles which will result in changed physical parameters in the postshock region. A self-consistent treatment of these effects is needed which is beyond the scope of this study. We only note that the kinematics of the postshock (X-ray emitting) plasma will be influenced most, thus, a continuing monitoring of the X-

ray emission from SNR 1987A with high spectral resolution (grating spectra) will be crucial in this respect.

Some deceleration in the bulk gas velocities was found between 2004 and 2007 from the grating spectra with very good photon statistics. The most important kinematic result from these data, however, was the finding that the bulk gas velocities inferred from the X-ray line profiles are too low to account for the postshock plasma temperatures derived from the spectral fits (Zhekov et al. 2005, 2006; Dewey et al. 2008; Zhekov et al. 2009). On the other hand, if efficient DSA operates in SNR 1987A, the total gas compression downstream from the shock front (i.e., in the X-ray emitting region) will be greater than its canonical value ($d_{ju,tot} > 4$). Such a result would imply that the bulk gas velocities in the space will be greater: $V_{bulk} = \frac{d_{ju,tot}-1}{d_{ju,tot}} V_{sh}$ (e.g., see also Chevalier 1983). If so, the X-ray spectral lines would be broader, in conflict to observations. These considerations support our assumption that the DSA in SNR 1987A is not very efficient.

This assumption gets additional support from the fact that the X-ray spectrum of SNR 1987A is dominated by emission from thermal plasma. Moreover, if, using the results from the fits to radio LCs (F_0, α), we extrapolate the NT radio spectrum to X-rays (equivalent to assuming efficient particle acceleration), the observed flux in the (3 - 10 keV) energy band is smaller than the one expected from relativistic electrons for the SNR 1987A age larger than 5,500

DAE. This result confirms that the DSA is not very efficient in producing relativistic particles with very high energies.

In the analysis presented here, we have argued that the physical picture in which the X-ray and NT radio emission from SNR 1987A originate in one and the same shock structure is realistic and capable of describing the observations. But, there is one important detail that emerges from the analyses of the X-ray and radio images of this object and needs more attention. If the picture adopted here is correct, the LCs in X-rays and radio may differ but the angular size of SNR 1987A in these spectral domains must be about the same. However, the image analyses so far indicate that the X-ray size of SNR 1987A is consistently smaller than its radio size. Because the object size is not measured directly but only after applying image-analysis techniques, such a difference might be attributed to the different methods used in analyzing the X-ray and radio images (Gaensler et al. 2007). On the other hand, a recent and more elaborate analysis of the radio images of SNR 1987A Ng et al. (2008) find that for times beyond 6,000 days after the explosion (6,000 - 7,600 DAE) the radius of the radio remnant is greater than 0.83 arcsec, *i.e.*, greater than the radius of the inner ring (see their Table 3). For the same period of time, the X-ray remnant still lies within the equatorial ring (Racusin et al. 2009).

Such an evolution of the radio size of SNR 1987A could be indeed important since it may indicate that the blast wave has propagated beyond the equatorial ring or the radio emission has some contribution from regions above and below it. The former was concluded by Ng et al. (2009) from their analysis of a single *Chandra HRC* (High Resolution Camera) image taken at 7736 DAE. They also derived a larger X-ray radius of SNR 1987A compared to the results from Racusin et al. (2009). But if this were the case, the radio (and or X-ray) emission should have started to decline similarly to the radio (X-ray) evolution soon after the explosion when the supernova ejecta was interacting with the BSG stellar wind. This is to be expected in the framework of the colliding stellar wind scenario for the origin of the ring system in this object because the gas beyond the inner ring is that produced by the wind of the red supergiant progenitor of SNR 1987A. Therefore, the emission measure in radio and X-rays must decrease with time (preshock number density will follow $1/r^2$ dependence). No indications of flux decline are seen both in the radio and X-ray LCs (e.g., see Ng et al. 2008; Zanardo et al. 2010; Racusin et al. 2009). And in order to explore the possibility for contribution from shocks above and below the equatorial plane, we may need to change our currently used geometrical models. Namely, models that assume deviation from a simple geometry of a torus, equatorial belt etc. might be a more realistic presentation of the actual interaction of the blast wave with the inner ring. We believe that the improving quality of the X-ray and radio data allow for adopting such models which in turn may provide us with valuable details about the physics of the interaction phenomenon.

An interesting aspect of our study is about what we can expect in the future, provided the physical picture adopted here is correct. As mentioned earlier (see § 3.1 and Fig. 1), the expansion velocity curve is successfully fitted for density profiles that may have different density contrast between the HII region and the maximum density of the smooth compo-

nent at the radius of the inner ring. This results in a considerably different time (t_{max}) when the blast wave will reach the radius of the equatorial ring and the X-ray (as well as the radio) emission will be at its maximum. We fitted all 14 CCD spectra simultaneously with the global RSS model for the cases with t_{max} between 10,000 and 15,000 DAE (with an increment of a 1000 DAE). These fits had similar quality ($\chi^2 = 1696 - 1734$) as our basic case ($t_{max} = 13,000$ DAE) discussed here in detail. As anticipated, it is not possible to discriminate between these cases just based on the available data and only future studies of the expansion velocity curve and other X-ray properties will help us in this respect. But it is worth mentioning that all these fits converge in the following.

Since the absolute value of the emission measure of the blast wave is constrained by the observed X-ray flux, in all the cases the nucleon number density near the inner radius of the HII region had values that are about the same: $n_{0,X} \approx 100 \text{ cm}^{-3}$ (as before we assumed an opening half-angle of $\sim 10^\circ$). From this it follows (see Fig 1) that the maximum density of the smooth component will be $n_{Ring} = 10^3 - 10^4 \text{ cm}^{-3}$ for the cases with t_{max} between 10,000 and 15,000 DAE. On the other hand, in all these cases we need to have dense clumps with about the same typical number density ($n_{clump} \approx 10^4 \text{ cm}^{-3}$) in order to match the observed X-ray spectra. We note that the clump density (in fact its contrast to the smooth component) controls the properties of the transmitted shocks (low temperature plasma). Interestingly, an indication of similar preshock number density ($\sim 10^4 \text{ cm}^{-3}$) was found also for the first hot spot discovered in the optical and UV. Using the line ratios of various forbidden lines, Pun et al. (2002) showed that the optical emission of Spot 1 comes from regions with densities of $n_e \sim 10^6 \text{ cm}^{-3}$ downstream radiative shocks that compressed the preshock gas by a factor of ≥ 100 . Thus, it seems conclusive that the HII region consists of dense clumps with similar properties and the density of its smooth component is not well constrained but it will be so depending on the time when the X-ray emission reaches its maximum.

It is worth noting that although our global RSS model is successful in matching both the expansion velocity curve of SNR 1987A and the evolution of its X-ray emission, it neglects the role of the reverse shock for the latter. In fact, the emission from the entire two-slab region (see § 2), that is of the shocked material between the forward and reverse shocks, is represented by the X-ray emission behind one fast shock: the evolving blast wave interacting with dense clumps. The validity of this seems justified given the good fits of our model to the X-ray spectra. So it could well be that the reverse shock produces unusually cool plasma, as it is a shock going through an almost neutral medium, in which magnetic turbulence, needed for collisionless shock heating, is damped. However, there are enough uncertainties in our model, but also concerning the general knowledge about collisionless shocks to remain cautious. We only note that the physics of the reverse shock in SNR 1987A is quite complicated to be addressed properly in a simplified physical picture we have adopted in this work.

As indicated by the infrared observations (e.g. Fig. 18 in Bouchet et al. 2006), the SN ejecta has become neutral already at times before the SNR 1987A reappearance in

the radio and X-rays ($\sim 1,000$ DAE). On the other hand, detection of $H\alpha$ and $Ly\alpha$ emission from the reverse shock (e.g. Michael et al. 2003; Heng et al. 2006) is a clear sign for presence of both neutral and ionized species. Thus, the reverse shock in SNR 1987A is not a standard collisional or collisionless shock in *plasma* but instead its shock front likely consists of a relatively broad transition zone where the ionization state changes from neutral (preshock ejecta material) into ionized (compressed ejecta plasma). As a result, it might well be that the electrons are not preheated in the shock front and their temperature is determined by the slow Coulomb collisions with protons and ions downstream the reverse shock which may not result in strong X-ray emission.

But, there is an interesting transformation of the reverse shock that we may witness in the near future. As suggested by Smith et al. (2005), the rapidly increasing X-ray flux from SNR 1987A should reach a level beyond which it will be capable of ionizing the neutral gas before it crosses the reverse shock. When this happens, the broad $H\alpha$ and $Ly\alpha$ emission will vanish and most importantly the reverse shock will transform from its current state into a collisionless shock, provided a magnetic field is present in the supernova ejecta.

The reverse shock transformation will have an interesting impact on the radio emission from SNR 1987A as well. Manchester et al. (2005) have suggested that the radio emission originates from the region behind the reverse shock. Park et al. (2005, 2007) noticed the close similarity in the shape of the light curves in the hard X-rays and radio and suggested that they may have a common origin. But, no signs of non-thermal X-ray emission from SNR 1987A have been found so far and we argued here that the global RSS picture is capable of explaining the radio and X-ray properties of SNR 1987A by assuming that the radio emission originates from the region behind the blast wave and not behind the reverse shock. On the other hand, once the supernova ejecta gas has been ionized before entering the reverse shock, the shock will become collisionless which will result in an efficient DSA of relativistic particles. After that moment, we can expect a more rapid increase of the non-thermal emission from SNR 1987A.

We note that although this picture is only qualitative and thus bears many uncertainties if it is correct, two observational evidences should be found in the future that can serve as a test for its validity. And it is important to note that these events must happen almost *simultaneously*: (i) the broad $H\alpha$ and $Ly\alpha$ emission from SNR 1987A will vanish; (ii) there will be a turn-up in the non-thermal radio emission from this object.

6.3 SNR 1987A vs. Young Supernova Remnants

Many young supernova remnants (Cas A, Kepler, Tycho, SN 1006, RCW 86) have been observed to contain non-thermal X-ray emission (e.g. Allen et al. 1999). These young remnants share other common features: non-thermal radio emission, signs of efficient (nuclear) cosmic ray (CR) acceleration and as a result from that they likely have amplified magnetic fields (for a discussion see Volk et al. 2005; Vink 2008). We note that the key signature of efficient DSA of relativistic particles in these objects is the presence of *non-thermal* X-ray emission. As already mentioned (§ 6.2),

SNR 1987A does *not* have that (or it is very weak) and its X-ray spectrum is successfully represented by thermal emission from shock heated plasma as analyses of both *Chandra* (Michael et al. 2002; Park et al. 2002, 2004, 2006; Zhekov et al. 2006, 2009) and *XMM-Newton* (Haberl et al. 2006; Heng et al. 2008) spectra have shown. This is also confirmed by our current analysis of the evolution of the *Chandra* CCD spectra of SNR 1987A.

It is then suggestive that the lack of non-thermal X-ray emission from SNR 1987A could be a signature of inefficient DSA of relativistic particles (protons and nuclear CR) and it might simply be explained by the fact that SNR 1987A is very young. Actually, its age is more than one order of magnitude smaller than that of the young SNRs showing those common features mentioned above. We can speculate that some time is probably needed before a SNR reaches a level when the DSA becomes very efficient and SNR 1987A has not yet entered that stage. On the other hand, old SNRs are not expected to have strong non-thermal X-ray emission since their shock velocities are decelerating (e.g. Völk et al. 2005). This can be an alternative explanation for the case of SNR 1987A that shows clear signs of shock deceleration at times $> 5,500$ DAE (Racusin et al. 2009; see also Fig. 1 and the lower right panel in Fig. 3). So, due to the presence of the inner equatorial ring and its HII region (a CSM with increasing outward density), the very young object, SNR 1987A, might mimic the evolution of old SNRs. But in either case, the fact of missing (or very weak) non-thermal X-ray emission probably indicates inefficient DSA in SNR 1987A.

Thus, the assumption of not very efficient DSA was adopted in our analysis here which also means that the magnetic field strength cannot be derived in a self-consistent manner as can be done for young SNRs with non-thermal X-ray emission (e.g. Volk et al. 2005). Due to this, our estimates (see § 6.1 also the lower panels in Fig. 8) use some fiducial value for the magnetic field strength at the inner radius of the HII region and we adopt the frozen-in conditions. The latter means that the field strength increases deeper in the inner ring. We note that in the interacting wind scenario, the origin of the magnetic field is likely related to the global field of the progenitor star during the BSG (and RSG) phase of its evolution. The adopted here value ($B_0 = 1$ mG) suggests that not a strong surface field is required if the global structure of the stellar magnetic field was according to the Parker's model (Parker 1958).

We note that such not strong magnetic fields are likely present in massive hot stars and the clear sign for this is the non-thermal radio emission detected from wide WR+O binaries (Dougherty & Williams 2000). This emission is identified with the colliding wind shock region in these objects and WR 140 and WR 147 are two classical examples of those. Interestingly, there are *no signs* of non-thermal component in the X-ray spectra of these objects which are successfully matched by thermal emission from plasma behind strong adiabatic shocks (e.g. for WR 140 see Zhekov & Skinner 2000; Pollock et al. 2005; for WR 147 see Zhekov 2007; Zhekov & Park 2010). Thus, a physical picture where strong adiabatic shocks produce thermal X-rays and the corresponding DSA of relativistic particles is not very efficient does not seem to be anything unique and it might well be

a reasonable assumption for the current evolution stage of SNR 1987A .

Finally, the ongoing monitoring of the X-ray emission from SNR 1987A will be very helpful in further constraining the physical picture described here. First, the continuous brightening of SNR 1987A will allow us to establish with higher certainty the level of non-thermal X-ray emission from this very young supernova remnant. We note that if strong (and increasing) non-thermal emission is detected, it will require considerable changes in the physical picture as we described it in this work. Second, the data from the monitoring observations will also provide us with detailed spectral information (grating data) that will reveal the evolution of the kinematics of the X-ray emitting plasma. We note that the RSS picture was proposed to explain the relatively narrow spectral lines in the grating spectra of SNR 1987A. As seen from Figs. 5 and 6, the contribution from the reflected shock to the total observed fluxes is not dominant even at times after 6,000 DAE which might be a deficiency from the poor spectral resolution in CCD spectra. Upgrading the available CCD data base with grating spectra, having good quality and spanning over long enough period of time, will allow us to test the global RSS model more rigorously by confronting its predictions with the actual evolution of the gas kinematics of the X-ray emitting plasma. This will also justify amendments to the model by taking into account the X-ray emission from the region behind the reverse shock. In turn, we can further improve our understanding of the exciting phenomenon of the birth of supernova remnant 1987A.

7 CONCLUSIONS

In this study, we continued to explore the validity of the reflected-shock structure picture in SNR 1987A. This picture assumes that the blast wave is interacting with the HII region in vicinity of the inner ring and when it encounters dense clump(s) a shock is transmitted into the clump(s) and a reflected shock forms that additionally compresses the shocked gas behind the blast wave. We adopted an improved version of the reflected-shock model (global RSS model) to test the RSS picture in SNR 1987A by making use of CCD spectra from the monitoring program with *Chandra*. The main results from this analysis are as follows.

1. The global RSS model is capable of matching both the X-ray expansion velocity curve (Racusin et al. 2009) as well as the X-ray spectra of SNR 1987A over its evolution for the last ten years or so. Moreover, extrapolating back in time the X-ray flux, the model is able to match the observed *ROSAT* fluxes from the time of the supernova reappearance in X-rays (1000-3000 DAE).

2. The evolution of the mean electron temperature behind the shocks shows a decrease with time of the electron temperature in the blast wave, while a slight increase with time is noticed for this parameter in the transmitted shock. The mean ratio of the electron to the mean plasma temperature is required to increase with the decrease of the velocity of the blast wave.

3. At early times, the soft (0.5-2 keV) X-ray flux of SNR 1987A was dominated by the blast wave but for times after ~ 6000 DAE the transmitted shock became dominant. This transition coincides with the steep upturn in the X-

ray LC reported by Park et al. (2005). Also, the emission measure of the hot plasma in the transmitted shock (as well as in the reflected shock) is increasing steeper than that for the blast wave for times after ~ 6400 DAE. All this is indicative of an ongoing penetration of the blast wave deeper in the equatorial ring debris.

4. Results from the X-ray analysis were used to explore the possibility that the X-rays and the non-thermal radio emission from SNR 1987A originate from the same shock structure (the blast wave). Using a simplified analysis, it was shown that this can indeed be the case, provided the particle acceleration mechanisms, that operate in the shocks in SNR 1987A, are not very efficient in producing relativistic particles with very high energies.

5. As a next step, the global RSS model could be used to obtain further constraints on the reflected-shock structure picture in SNR 1987A by analyzing X-ray spectra with good spectral resolution once the available data cover a long enough time interval of the SNR 1987A evolution. We believe that this will allow us to improve our understanding of the underlying physics and to build a more realistic picture and model of this fascinating phenomenon: the birth and evolution of supernova remnant 1987A.

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REFERENCES

- Allen, G.E., Gotthelf, E.V., & Petre, R. 1999, in Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City), 3, 480
- Anders E., Grevesse N., 1989, *Geochimica et Cosmochimica Acta*, 53, 197
- Arnaud, K.A. 1996, in Jacoby G., Barnes, J. eds., ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems, Astron. Soc. Pac., San Francisco, 17
- Ball, L., Crawford, D. F., Hunstead, R. W., Klammer, I., McIntyre, V. J. 2001, *ApJ*, 549, 599
- Bell, A.R. 1978, *MNRAS*, 182, 147
- Berezhko, E.G. & Ksenofontov, L.T. 2006, *ApJ*, 650, L59
- Beuermann, K., Brandt, S., & Pietsch, W. 1994, *A&A*, 281, L45
- Blondin, J.M. & Lundqvist, P. 1993, *ApJ*, 405, 337
- Borkowski, K. J., Blondin, J. M., & McCray, R. 1997a, *ApJ*, 476, L31
- Borkowski, K. J., Blondin, J. M., & McCray, R. 1997b, *ApJ*, 477, 281
- Borkowski, K. J., Lyerly, W.J., & Reynolds, S.P. 2001, *ApJ*, 548, 820
- Bouchet, P., De Buizer, J.M., Suntzeff, N.B., Danziger, I.J., Hayward, T.L., Telesco, C.M., & Peckham, C. 2004, *ApJ*, 611, 394
- Bouchet, P. et al. 2006, *ApJ*, 650, 212
- Burrows, C.J. et al. 1995, *ApJ*, 452, 680
- Burrows, D. N. et al. 2000, *ApJ*, 543, L149
- Chevalier, R.A. 1982, *ApJ*, 258, 790
- Chevalier, R.A. 1983, *ApJ*, 272, 765

- Chevalier, R.A. & Dwarkadas, V.V. 1995, *ApJ*, 452, L45
- Crotts, A.P.S. & Heathcote, S.R. 1991, *Nature*, 350, 683
- Dewey D., Zhekov, S.A., McCray, R., & Canizares, C.L. 2008, *ApJ*, 676, L131
- Dougherty, S.M. & Williams, P.M. 2000, *MNRAS*, 319, 1005
- Duffy, P., Ball, L. & Kirk, J.G. 1995, *ApJ*, 447, 364
- Dwek, E. et al. 2008, *ApJ*, 676, 1029
- Eastman, R.G. & Kirshner, R.P. 1989, *ApJ*, 347, 771
- Gaensler, B.M., Manchester, R. N., Staveley-Smith, L., Tzioumis, A. K., Reynolds, J. E., Kesteven, M. J. 1997, *ApJ*, 479, 845
- Gaensler, B.M., Staveley-Smith, L., Manchester, R. N., Kesteven, M. J., Ball, L., Tzioumis, A. K. 2007, in AIP Conf. Proc. 937, *Supernova 1987A: 20 Years After. Supernovae and Gamma-Ray Bursters*, eds. S. Immler, K.W. Weiler, & R. McCray (New York, AIP), 86
- Ghavamian, P., Raymond, J., Smith, R.C., Hartigan, P. 2001 *ApJ*, 547, 995
- Gorenstein, P., Hughes, J. P., & Tucker, W.H. 1994, *ApJ*, 420, L25
- Groningsson, P., Fransson, C., Lundqvist, P., Nymark, T., Lundqvist, N., Chevalier, R., Leibundgut, B., Spyromilio, J. 2006, *A&A*, 456, 581
- Groningsson, P., Fransson, C., Leibundgut, B., Lundqvist, P., Challis, P., Chevalier, R. A., Spyromilio, J. 2008, *A&A*, 492, 481
- Haberl, F., Geppert, U., Aschenbach, B. & Hasinger, G. 2006, *A&A*, 460, 811
- Hasinger, G., Aschenbach, B., & Trümper, J. 1996, *A&A*, 312, L9
- Heng, K. et al. 2006, *ApJ*, 644, 959
- Heng, K., Haberl, F., Aschenbach, B., & Hasinger, G. 2008, *ApJ*, 676, 361
- Hughes, J.P., Hayashi, I., & Koyama, K. 1998, *ApJ*, 505, 732
- Jakobsen, P. et al. 1991, *ApJ*, 369, L63
- Lawrence, S.S., Sugerman, B.E., Bouchet, P., Crotts, A.P.S., Uglesich, R., Heathcote, S. 2000, *ApJ*, 537, L123
- Lundqvist, P., & Fransson, C. 1996, *ApJ*, 464, 924
- Luo, D. & McCray, R. 1991, *ApJ*, 379, 659
- Manchester, R.N., Gaensler, B. M., Wheaton, V. C., Staveley-Smith, L., Tzioumis, A. K., Bizunok, N. S., Kesteven, M. J., Reynolds, J. E. 2002, *Publ. Astron. Soc. Australia*, 19, 207
- Manchester, R.N., Gaensler, B. M.; Staveley-Smith, L.; Kesteven, M. J.; Tzioumis, A. K. 2007, *ApJ*, 628, L131
- McCray, R. 2007, in AIP Conf. Proc. 937, *Supernova 1987A: 20 Years After. Supernovae and Gamma-Ray Bursters*, eds. S. Immler, K.W. Weiler, & R. McCray (New York, AIP), 3
- Michael, E. et al. 2002, *ApJ*, 574, 166
- Michael, E. et al. 2003, *ApJ*, 593, 809
- Morris, T. & Podsiadlowski, P. 2007, *Science*, 315, 1103
- Ng, C-Y., Gaensler, B. M., Staveley-Smith, L., Manchester, R. N.; Kesteven, M. J., Ball, L., Tzioumis, A. K. 2008, *ApJ*, 684, 481
- Ng, C-Y, Gaensler, B. M., Murray, S. S., Slane, P. O., Park, S., Staveley-Smith, L., Manchester, R. N., Burrows, D. N. 2009, *ApJ*, 706, L100
- Park, S., Burrows, D.N., Garmire, G. P., McCray, R., Racusin, J.L., & Zhekov, S. A. 2007, in AIP Conf. Proc. 937, *Supernova 1987A: 20 Years After. Supernovae and Gamma-Ray Bursters*, eds. S. Immler, K.W. Weiler, & R. McCray (New York, AIP), 43
- Park, S., Burrows, D.N., Garmire, G. P., Nowsek, J.A., McCray, R., Michael, E., & Zhekov, S.A. 2002, *ApJ*, 567, 314
- Park, S., Zhekov, S. A., Burrows, D.N., Garmire, G. P., & McCray, R. 2004 *ApJ*, 610, 275
- Park, S., Zhekov, S. A., Burrows, D.N., & McCray, R. 2005, *ApJ*, 634, L73
- Park, S., Zhekov, S. A., Burrows, D.N., & McCray, R. 2006, *ApJ*, 646, 1001
- Parker, E.N. 1958, *ApJ*, 128, 664
- Pollock, A.M.T., Corcoran, M.F., Stevens, I.R., & Williams, P.M. 2005, *ApJ*, 629, 482
- Potter, T.M. et al. 2009, *ApJ*, 705, 261
- Pun, C. S. J. et al. 2002, *ApJ*, 572, 906
- Racusin, J.L., Park, S., Zhekov, S., Burrows, D.N., Garmire, G.P., McCray, R. 2009, *ApJ*, 703, 1752
- Russel, S. C., & Dopita, M. A. 1992, *ApJ*, 384, 508
- Rybicki, G.B. & Lightman, A.P. 1979, *Radiative Processes in Astrophysics* (New York: Wiley), 167
- Smith, N., Zhekov, S.A., Heng, K., McCray, R., Morse, J.A., & Gladders, M. 2005, *ApJ*, 635, L41
- Sonnerborn, G. et al. 1998, *ApJ*, 492, L139
- Staveley-Smith et al. 1992, *Nature*, 355, 147
- Staveley-Smith, L., Briggs, D. S., Rowe, A. C. H., Manchester, R. N., Reynolds, J. E., Tzioumis, A. K., Kesteven, M. J. 1993, *Nature*, 366, 136
- Staveley-Smith, L., Gaensler, B.M., Manchester, R.N., Ball, L., Kesteven, M.J., Tzioumis, A.K. 2007, in AIP Conf. Proc. 937, *Supernova 1987A: 20 Years After. Supernovae and Gamma-Ray Bursters*, eds. S. Immler, K.W. Weiler, & R. McCray (New York, AIP), 96
- Sugerman, B. E. K., Lawrence, S. S., Crotts, A. P. S., Bouchet, P., & Heathcote, S. R. 2002, *ApJ*, 572, 209
- Suzuki, T., Shigeyama, T., & Nomot, K. 1993, *A&A*, 274, 883
- Turtle, A.J., Campbell-Wilson, D., Manchester, R.N., Staveley-Smith, L., Kesteven, M.J. 1990, *IAU Circ.* 5086, 2
- Vink, J. 2009, in AIP Conf. Proc. 1085, *High Energy Gamma-Ray Astronomy*, 169
- Völk, H.J., Berezhko, E.G., & Ksenofontov, L.T. 2005, *A&A*, 433, 229
- Wampler, E.J., Wang, L., Baade, D., Banse, K., D'Odorico, S., Gouffes, C., Tarengi, M. 1990, *ApJ*, 362, L13
- Wang, L. & Mazzali, 1992, *Nature*, 355, 58
- Zanardo, G. et al. 2010, *ApJ*, 710, 1515
- Zhekov, S.A. 2007, *MNRAS*, 382, 886
- Zhekov, S. A., McCray, R., Borkowski, K. J., Burrows, D. N. & Park, S. 2005, *ApJ*, 628, L127
- Zhekov, S. A., McCray, R., Borkowski, K.J., Burrows, D.N., & Park, S. 2006, *ApJ*, 645, 293
- Zhekov, S. A., McCray, R., Dewey, D., Canizares, C.R., Borkowski, K.J., Burrows, D.N., & Park, S. 2009, *ApJ*, 692, 1190
- Zhekov S.A. & Park, S. 2010, *ApJ*, 709, L119
- Zhekov S.A. & Skinner, S.L. 2000, *ApJ*, 538, 808

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